Search for New Phenomena in $t\bar{t}$ Events with Large Missing Transverse Momentum in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

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A search for new phenomena in $t\bar{t}$ events with large missing transverse momentum in proton-proton collisions at a center-of-mass energy of 7 TeV is presented. The measurement is based on 1.04 fb^{-1} of data collected with the ATLAS detector at the LHC. Contributions to this final state may arise from a number of standard model extensions. The results are interpreted in terms of a model where new top-quark partners are pair produced and each decay to an on-shell top (or antitop) quark and a long-lived undetected neutral particle. The data are found to be consistent with standard model expectations. A limit at 95% confidence level is set excluding a cross section times branching ratio of 1.1 pb for a top-partner mass of 420 GeV and a neutral particle mass less than 10 GeV. In a model of exotic fourth generation quarks, top-partner masses are excluded up to 420 GeV and neutral particle masses up to 140 GeV.

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The top quark holds great promise as a probe for new phenomena at the TeV scale. It has the strongest coupling to the standard model Higgs boson, and as a consequence it is the main contributor to the quadratic divergence in the Higgs boson mass. Thus, assuming the "naturalness" hypothesis of effective quantum field theory, light top partners (with masses below about 1 TeV) should correspond to one of the most robust predictions of solutions to the hierarchy problem.

In this Letter, a search is presented for pair-produced exotic top partners $T\bar{T}$, each decaying to a top quark and a stable, neutral weakly interacting particle A_0, which in some models may be its own antiparticle. The final state for such a process ($T\bar{T} \to t\bar{t}A_0A_0$) is identical to $t\bar{t}$, though with a larger amount of missing transverse momentum (E_T^{miss}) from the undetected A_0 pair. In supersymmetry models with R-parity conservation, T is identified with the stop squark and A_0 with the lightest supersymmetric particle, the neutralino (χ_0) [1] or the gravitino ($\tilde{G}$) [2]. The $t\bar{t} + E_T^{\text{miss}}$ [3] signature appears in a general set of dark matter motivated models, as well as in other standard model (SM) extensions, such as the above-mentioned supersymmetry models, little Higgs models with T-parity conservation [4–6], models of universal extra dimensions (UED) with Kaluza-Klein parity [7], models in which baryon and lepton number conservation arises from gauge symmetries [8], or models with third-generation scalar leptoquarks. Many of these models provide a mechanism for electroweak symmetry breaking and predict dark matter candidates, which can be identified indirectly through their large E_T^{miss} signature.

The search is performed in the $t\bar{t}$ single-lepton channel where one W boson produced by the top pair decays to a lepton-neutrino pair ($W \to \ell\nu$, including τ decays to e or μ) and the other W boson decays to a pair of quarks ($W \to q\bar{q}'$), resulting in a final state with an isolated lepton of high transverse momentum, four or more jets, and large E_T^{miss}. The observed yield in this signal region is compared with the SM expectation. In the absence of signal an upper limit on the cross-section times branching ratio BR($T\bar{T} \to t\bar{t}A_0A_0$) is quoted. In the model of exotic fourth generation up-type quarks [9] the $T\bar{T}$ production cross section is predicted to be approximately 6 times higher than for stop squarks with a similar mass [3], due to the multiple spin states of two T's compared to scalar stops. For this model the cross-section limits are converted to an exclusion curve in the T vs A_0 mass parameter space. A search for these exotic top-quark partners was performed in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV by the CDF Collaboration [10]. The data were found to be consistent with SM expectations. A 95% confidence level limit was set excluding a top-partner mass of 360 GeV for a neutral particle mass less than 100 GeV. A recent update by CDF in the all-jets channel excludes top-partner masses up to 400 GeV [11].

The ATLAS detector [12] consists of an inner detector tracking system (ID) surrounded by a superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The ID consists of pixel and silicon microstrip detectors inside a transition radiation tracker which provide tracking in the region $|\eta| < 2.5$ [13]. The electromagnetic calorimeter is a lead-liquid argon (LAr) detector in the barrel ($|\eta| < 1.475$) and end cap ($1.375 < |\eta| < 3.2$) regions. Hadron calorimetry is based on two different detector technologies.

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The barrel ($|\eta| < 0.8$) and extended barrel ($0.8 < |\eta| < 1.7$) calorimeters are composed of scintillator and steel, while the hadronic end cap calorimeters ($1.5 < |\eta| < 3.2$) are copper and LAr. The forward calorimeters ($3.1 < |\eta| < 4.9$) are instrumented with copper and LAr and tungsten and LAr, providing electromagnetic and hadronic energy measurements, respectively. The MS consists of three large superconducting toroids with 24 coils, a system of trigger chambers, and precision tracking chambers which provide muon momentum measurements up to $|\eta|$ of 2.7.

The analysis is based on data recorded by the ATLAS detector in 2011 using 1.04 fb^{-1} of integrated luminosity. The data were collected using electron and muon triggers. Requirements that ensure the quality of beam conditions, detector performance, and data are imposed. Monte Carlo (MC) event samples with full ATLAS detector simulation [14] based on the GEANT4 program [15] and corrected for all known detector effects are used to model the signal process and most of the backgrounds. The multijet background is modeled using data control samples rather than the simulation. The background sources are separated into four main categories according to their importance: dilepton $t\bar{t}$ (where both W bosons decay to a lepton-neutrino pair: $W \rightarrow \ell\nu$); single-lepton $t\bar{t}$ and $W +$ jets; multijet production; and other electroweak processes, such as diboson production, single top, and $Z +$ jets. The $t\bar{t}$ and single top samples are produced with MC@NLO [16], while the $W +$ jets and $Z +$ jets samples are generated with ALPGEN [17]. HERWIG [18] is used to simulate the parton shower and fragmentation, and JIMMY [19] is used for the underlying event simulation. The diboson background is simulated using HERWIG. The $t\bar{t}$ cross section is normalized to approximate next-to-next-to-leading order (NNLO) calculations [20], the inclusive $W +$ jets and $Z +$ jets cross sections are normalized to NNLO predictions [21], and the cross sections of the other backgrounds are normalized to NLO predictions [22]. Additional corrections to the MC predictions are extracted from the data, as described below.

Electron and muon candidates are selected as for other recent ATLAS top-quark studies using the single-lepton signature [23]. Jets are reconstructed using the anti-k_t [24] algorithm with the distance parameter $R = 0.4$. To take into account the differences in calorimeter response to electrons and hadrons, a p_T- and η-dependent factor, derived from simulated events and validated with data, is applied to each jet to provide an average energy scale correction [25] corresponding to the energies of the reconstructed particles.

In the calorimeter, the energy deposited by particles is reconstructed in three-dimensional clusters. These clusters are calibrated according to the associated reconstructed high-p_T object. The energy of these clusters is summed vectorially, and projections of this sum in the transverse plane correspond to the negative of the $E_T^{\rm miss}$ components [26]. Clusters not associated with any high-p_T object and muons reconstructed in the MS are also included in the $E_T^{\rm miss}$ calculation.

Events are selected with exactly one isolated electron or muon that passes the following kinematic selection criteria. Electrons are required to satisfy $E_T > 25$ GeV and $|\eta| < 2.47$. Electrons in the region between the barrel and the end cap electromagnetic calorimeters ($1.37 < |\eta| < 1.52$) are removed. Muon candidates are required to satisfy $p_T > 20$ GeV and $|\eta| < 2.5$. These selected leptons lie in the efficiency plateau of the single-lepton triggers. Only events with four or more reconstructed jets with $p_T > 25$ GeV and $|\eta| < 2.5$ are selected. To reduce the single-lepton $t\bar{t}$ and $W +$ jets background, events are required to have $E_T^{\rm miss} > 100$ GeV and $m_T > 150$ GeV, where m_T is the transverse mass of the lepton and $E_T^{\rm miss}$ [27]. Events with either a second lepton candidate with $p_T > 15$ GeV or a track with $p_T > 12$ GeV, with no other tracks with $p_T > 3$ GeV within $\Delta R = 0.4$ ($\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$), are rejected in order to reduce the contribution from $t\bar{t}$ dilepton events. In particular, the isolated track veto is useful in reducing single-prong hadronic τ decays in $t\bar{t}$ dilepton events. A summary of the background estimates and a comparison with the observed number of selected events passing all selection criteria are shown in Table I. A total yield of 101 ± 16 events is expected from SM sources, and 105 events are observed in data. The background composition is similar in the electron and muon channels.

The dominant background arises from $t\bar{t}$ dilepton final states in which one of the leptons is not reconstructed, is outside the detector acceptance, or is a τ lepton. In all such cases, the $t\bar{t}$ decay products include two high-p_T neutrinos, resulting in large $E_T^{\rm miss}$ and m_T tails. In MC simulation, the second lepton veto removes 45% of the dilepton $t\bar{t}$ and 10% of the single-lepton $t\bar{t}$ in the signal region. The veto performance is validated in the data in several control regions both enhanced and depleted in dilepton $t\bar{t}$. Based on the data-MC agreement in these control regions a 10% uncertainty is assigned to the veto efficiencies modeled in MC simulation.

TABLE I. Summary of expected SM yields including statistical and systematic uncertainties compared with the observed number of events in the signal region.

Source	Number of events
Dilepton $t\bar{t}$	62 ± 15
Single-lepton $t\bar{t}/W +$ jets	33.1 ± 3.8
Multijet	1.2 ± 1.2
Single top	3.5 ± 0.8
$Z +$ jets	0.9 ± 0.3
Dibosons	0.9 ± 0.2
Total	101 ± 16
Data	105

The next largest background comes from single-lepton sources, including W + jets and $t\bar{t}$ with one leptonic W decay. Both the normalization and the shape of the m_T distribution for this combined background are extracted from the data. First, the yield of the single-lepton background estimated from simulation is normalized in the control region 60 GeV $< m_T <$ 90 GeV to the data which gives a correction of $(-5 \pm 3)\%$. Next, the shape of the m_T distribution in MC is compared with data in various signal-depleted control regions, where events satisfy the signal event selection but have fewer than four jets. In these control samples events with identified b jets, based on lifetime b tagging [23], are rejected in order to reduce the dilepton $t\bar{t}$ background, such that these control samples are dominated by W + jets events; the corresponding loss of single-lepton $t\bar{t}$ from this b-jet veto is accounted for in the systematic uncertainties. A comparison between data and MC in this control region shows that MC systematically underestimates the tails of the m_T distribution above 150 GeV, and a shape correction is derived that results in a $(15 \pm 10)\%$ increase of the expected yield in the signal region.

The multijet background is extracted from the data using techniques similar to those described in Ref. [23]. The techniques exploit the fact that the lepton isolation efficiency is different in signal and multijet events. In both lepton channels the contribution to the signal region is consistent with zero.

The contributions from single top, diboson production (WW, WZ, and ZZ), and Z + jets are estimated using MC simulation, normalized to the theoretical cross section and total integrated luminosity.

The background yields estimated from MC simulated events are affected by systematic uncertainties related to the modeling of detector performance, reconstruction, and object identification. The largest of these uncertainties are from the jet energy scale [25] (approximately 5%–7% on the jet p_T, including a contribution from pileup effects, leading to an 11% uncertainty on the background event yield), and from the performance of the second lepton veto in dilepton $t\bar{t}$ (10%). Other uncertainties include those on the lepton momentum scales and trigger and reconstruction efficiencies. Lepton momentum scales and resolutions are determined from fits to the Z-mass peak. Trigger and reconstruction efficiencies are evaluated using tag-and-probe measurements in $Z \rightarrow e^+e^-$ or $Z \rightarrow \mu^+\mu^-$ events. To evaluate the effect of lepton momentum and jet energy scale uncertainties, the E_T^{miss} and m_T are recalculated for each uncertainty on selected objects. Other small uncertainties affecting the E_T^{miss} calculation are due to multiple pp interactions, jets with p_T below 20 GeV, and calorimeter clusters that are not associated to a selected object [28]. Additionally, theoretical cross-section uncertainties from choice of scales and parton distribution functions are considered for these background sources, as are the effects of using alternative MC generators, shower models, and initial- and final-state radiation tunings [23]. Finally, the 3.7% uncertainty on the integrated luminosity [29] is applied to each background source.

The systematic uncertainties applied to data-driven backgrounds are determined from the data. The dominant uncertainty for single-lepton backgrounds is due to the $(15 \pm 10)\%$ shape correction, and is derived from the variation in the measured correction in different control regions and from uncertainties in the b-tagging efficiency. The uncertainty on the single-lepton normalization of $(-5 \pm 3)\%$ includes equal contributions from limited data statistics in the W mass region and expected differences between the W + jets and single-lepton $t\bar{t}$ contributions to the signal and control regions. A 100% systematic uncertainty is assigned to the small estimated multijet yield.

The expected and observed event yields are consistent within statistical and systematic uncertainties. Therefore, the results are interpreted as a limit on the possible non-SM contribution to the selected sample. A model involving pair production of heavy quarklike objects ($T\bar{T}$), each forced to decay to a top quark and a scalar neutral A_0, is chosen to establish these limits.

MADGRAPH [30] is used to simulate the signal process with the parton distribution function set CTEQ6L1 [31], and PYTHIA [32] is used to simulate the parton shower and fragmentation. A grid of T and A_0 masses is generated with 300 GeV $\leq m(T) \leq$ 450 GeV and 10 GeV $\leq m(A_0) \leq$ 150 GeV. Each sample is normalized to the cross section calculated at approximate NNLO in QCD using HATHOR [33], ranging from 8.0 pb for a T mass of 300 GeV to 0.66 pb for a T mass of 450 GeV. Using this grid of signal samples, the efficiency times acceptance for the $T\bar{T}$ signal model is parametrized as a function of the T and A_0 masses to generate the expected signal event yield for any pair of masses. The combined acceptance times signal selection efficiency varies between 3% and 5% for small A_0 masses and decreases to between 2% and 4% for larger A_0 masses.

All common systematic uncertainties for MC-based backgrounds are applied to this signal model. These include the uncertainties on the jet energy scale, lepton reconstruction efficiencies and scales, integrated luminosity, and the dilepton veto efficiency. Overall, the systematic uncertainty on the signal acceptance times efficiency varies between 11% and 14%, and is largest for those samples with a T-A_0 mass difference closest to the top quark mass. The theoretical uncertainties on the signal cross section vary between 10% to 15% and originate mainly from the choice of scales ($m_T/2 < \mu_R = \mu_F < 2m_T$, where μ_R and μ_F are the renormalization and factorization scale) and parton distribution functions.

The E_T^{miss} and m_T distributions for data are shown in Fig. 1 and compared with the background and signal predictions. There is no significant evidence of an excess over the SM prediction, and the kinematics are well modeled.

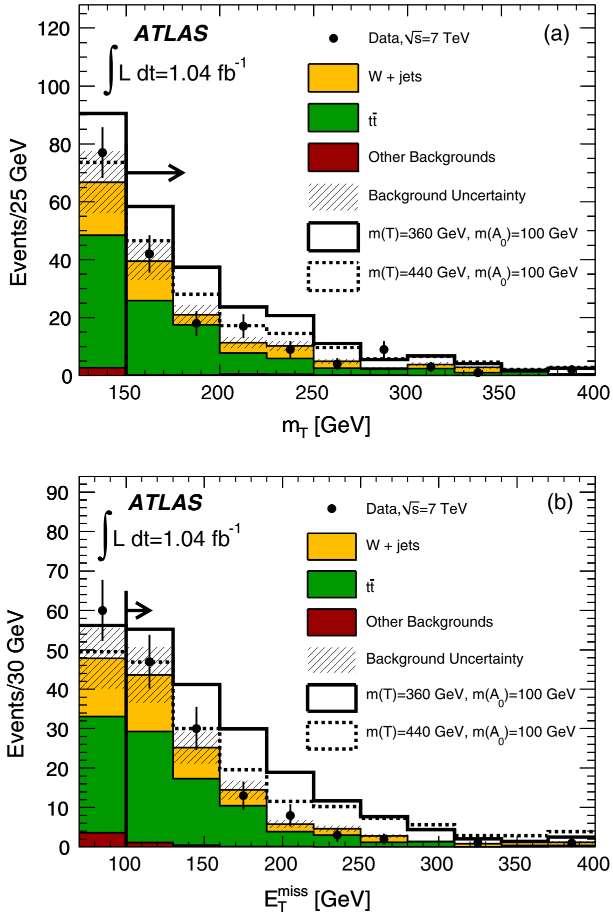

FIG. 1 (color online). (a) Transverse mass of the lepton and missing energy and (b) E_T^{miss} after applying all selection criteria except the cut on the variable shown. MC background contributions are stacked on top of each other and normalized according to the data-driven corrections discussed in the text. The lines with the arrows indicate the selection criteria that define the signal region ($m_T > 150$ GeV and $E_T^{\text{miss}} > 100$ GeV). "Other Backgrounds" includes both multijet backgrounds and $Z +$ jets, single top, and diboson production. Expectations from two signal mass points are stacked separately on top of the SM background. The last bin includes the overflow.

From the observed event yield and the predicted signal and background event yields after all cuts, a frequentist confidence interval on the signal hypothesis is calculated for various assumed T and A_0 masses, assuming Gaussian systematic uncertainties. Correlations between signal and background uncertainties are included. Figure 2 shows the region of parameter space excluded at the 95% confidence level. As the mass difference between the T and A_0 approaches the top-quark mass, the A_0 contributes less momentum to the E_T^{miss}, and signal becomes indistinguishable from SM $t\bar{t}$. Assuming a $T\bar{T} \to t\bar{t}A_0A_0$ branching ratio of 100%, signal points with T mass up to 420 GeV are excluded at the 95% confidence level for an A_0 mass below 10 GeV, as are signal points with 330 GeV $< m(T) <$ 390 GeV for an A_0 mass below 140 GeV. Figure 3 shows

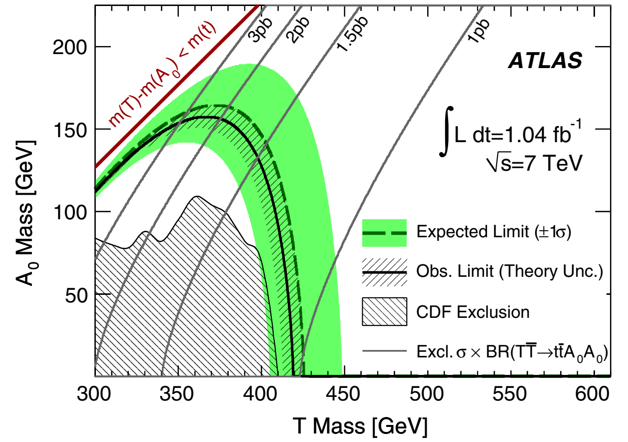

FIG. 2 (color online). Excluded region (under the curve) at the 95% confidence level as a function of T and A_0 masses, compared with the CDF exclusion [10,11]. Theoretical uncertainties on the $T\bar{T}$ cross section are not included in the limit, but the effect of these uncertainties is shown. The gray contours show the excluded cross-section times branching ratio as a function of the two masses.

the cross-section times branching ratio excluded at the 95% confidence level versus T mass, for an A_0 mass of 10 GeV. A cross-section times branching ratio of 1.1 (1.9) pb is excluded at the 95% confidence level for a T mass of 420 (370) GeV and an A_0 mass of 10 (140) GeV. The estimated acceptance times efficiency for spin-$\frac{1}{2}$ $T\bar{T}$ models is consistent within systematic uncertainties with that for scalar models, such as pair production of stop squarks (with a $t\bar{t}\chi_0\chi_0$ final state) or third-generation leptoquarks (with a $t\bar{t}\nu_\tau\bar{\nu}_\tau$ final state). The cross-section limits presented in Fig. 3 are therefore approximately valid for such models, although the predicted cross section is typically below the current sensitivity.

In summary, in 1.04 fb^{-1} of data in pp collisions at a center-of-mass energy of 7 TeV, there is no evidence of an

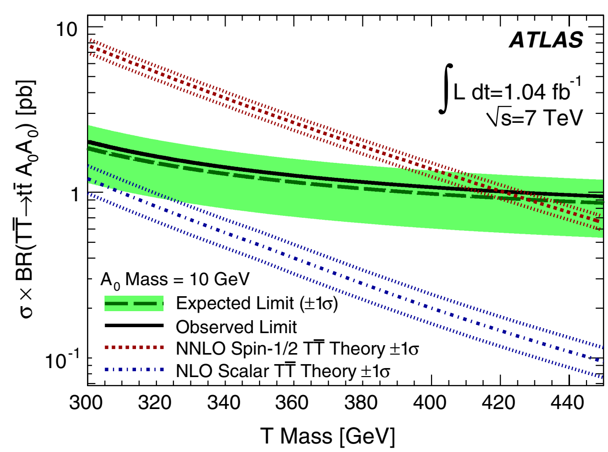

FIG. 3 (color online). Cross-section times branching ratio excluded at the 95% confidence level versus T mass for an A_0 mass of 10 GeV. Theoretical predictions for both spin-$\frac{1}{2}$ and scalar T pair production are also shown.

excess of events with large E_T^{miss} in a sample dominated by $t\bar{t}$ events. Using a model of pair-produced quarklike objects decaying to a top quark and a heavy neutral particle, a limit is established excluding masses of these top partners up to 420 GeV and stable weakly interacting particle masses up to 140 GeV (see Fig. 2). In particular, a cross-section times branching ratio of 1.1 pb is excluded at the 95% confidence level for $m(T) = 420$ GeV and $m(A_0) = 10$ GeV. The cross-section limits are approximately valid for a number of models of new phenomena.

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